Open Pit Mining through a River Sand in a Subarctic Climate using a Mechanically Stabilized Earth Wall

M. Rougier Golder Associates Ltd, Mississauga, Canada
P. Merry Golder Associates Ltd, Mississauga, Canada
L. Castro Golder Associates Ltd, Mississauga, Canada

Abstract
The performance of soils exposed on open pit slopes is adversely affected by subarctic climatic conditions. This paper outlines a case study of how geotechnical conditions were reassessed from the design stage and remedial measures implemented to control erosion and maintain long term stability at the De Beers Canada's Victor Diamond Mine open pit, located in northern Ontario.

During development of the Victor pit, exposed deposits of sands on upper slopes were encountered where only limestone bedrock had been anticipated. Because of their weakly cemented characteristics, the sands were excavated without blasting, using the bench geometry intended for the disturbed limestone domain on the perimeter of the kimberlite pipe. Performance was always initially good, due to the sand's weak cementation and also by the below freezing temperatures. With each spring freshet and significant rain event the slopes degraded, sloughed and eroded causing concerns for haul road traffic below and for the performance of overlying glacio-marine clays.

The remedial measures considered in the evaluation included; water diversions, slope flattening, laybacks, various types of buttresses and rip rap. The remedial measures were organized in the form of a decision matrix that was used to address exposed or possible future sand zone exposures, taking into account their size, accessibility, and location in relation to the overburden slopes and ramp. The case study describes the buttressing of a 100m long exposure with an additional design challenge when locally the sand was two benches (i.e. 20m) deep and displaying cross-beds, referred to as the River Sand Lens.

1 Introduction
This paper documents the experience from assessment, design and construction of remedial measures for transported sediments that were unexpectedly exposed on slopes the De Beers Canada Victor Diamond Mine located in Northern Ontario (Figure 1). The behaviour and material properties of the sands were determined based on slope performance and back analyses.

In the two years prior to the exposure of the river sand lens, numerous narrower sand zones, with the appearance of sub-vertical cracks filled with sand, were encountered. Even when the unfrozen these early exposures remained stable if kept dry, but soon degraded due to run-off and precipitation. This precedent experience was the technical basis for back analyses characterization of the anticipated behaviour of the much larger and more significant river sand zone encountered later. Given the susceptibility of the sand to erosion, preferred remedial options were discussed in the context of slope stabilization and control of surface water runoff.

2 Victor mine
At the time of the study (2009-2010), the Victor Diamond mine was a circular pit with final wall slopes ranging from 30 m to 50 m deep over that period. The pit floor exposed kimberlite of the Victor Main pipe and the pit walls exposed overburden and disturbed limestone. The pit was being actively dewatered by a ring of
dewatering wells, with sufficient drawdown such that the pit floor, the exposed rock slopes and the unexpected sand zones within them could be considered dry. Surface run-off from direct precipitation or run-off was  uncontrolled, and allowed to flow over the overburden and bedrock slopes. The need to control the movement of significant amounts of clay / overburden into the open pit (H.Q. Golder, 1972) was not addressed during the early stages of mining.

Bench elevations in the pit followed a mine convention such that elevations increase with depth.

- **Ground surface:** 100m level
- **Base of clays / top of bedrock (varies):** 120 m level
- **Base of main extent of the River Sand Lens:** 130m level
- **Base of lower portion of River Sand Lens, south end:** 140m level

![Figure 1. Victor Mine project location.](image)

3 **Open pit engineering geology**

3.1 **Muskeg**

The topography at Victor is flat, with the surface vegetation on the perimeter of the Victor Mine Open Pit consisting of the muskeg terrain (also referred to as bog land) that are common in the boreal regions of Canada. Muskeg has a near-surface water table and the muck and organics within it have very high water contents. With respect to slope design, this terrain, combined with sub-arctic climate, can store then release a great amount of snowmelt and precipitation during the spring freshet (Figure 2).

3.2 **Clays**

Underlying the muskeg, the overburden exposed on the upper slope of the Victor Open pit is glacio-marine clay, ranging in depth from 5m to 20m, with local areas of discontinuous permafrost. Initial clay slopes were excavated at 2.5:1 or steeper, benched, and were unstable where the thickness of clay was greater than 5m to 10m. Field investigations and back analysis of slope performance suggests that the clays can be described as
saturated, soft, with an undrained shear strength of $Cu=20kPa$, with a stronger basal layer at depth. For the deepest exposures, $>=20m$ deep, optimal performance was achieved by regrading unbenched slopes with slope angles of $4H:1V$. As part of the remedial measure developed for the sand zones, surface water diversion and herring-bone drains were recommended and implemented to divert run-off away from the clays and the underlying rock slopes.

### 3.3 Upper bedrock
Underlying the marine clays, limestone of the Silurian Age Attawapiskat formation is exposed on the pit slopes. The limestone can be described as horizontally bedded and moderately strong to strong. The RQD of the rock mass improves with depth below top of rock and decreases with proximity to the kimberlite pipe (the disturbed limestone zone). The low RQD rock mass adjacent to the kimberlite pipe represents the disturbed limestone zone.

![Aerial photograph of the Victor Mine showing the open pit and surrounding muskeg.](image)

### 3.4 Sand lenses
The initial exposure of the sand lenses occurred in 2008, when the pit locally deepened below the interpreted base of overburden. Rock slopes in the disturbed limestone / weathered limestone zones adjacent to the sand lenses were excavated with a 10 m bench height, 8 m design catch berm width and 45 degree inter-ramp angle.

Because of their weakly cemented characteristics, the sands were excavated without blasting, using the bench geometry intended for the disturbed limestone zone on the perimeter of the kimberlite pipe. Performance was always initially good, due to the sand’s weak cementation and below freezing temperatures. During the 2009 spring freshet and significant 2009 rain events, the slopes degraded, sloughed and eroded causing concerns for haul road traffic below and for the performance of overlying glacio-marine clays (Figure 3), as they could be undercut by the progression of the sand lens erosion. Instability involving large sand lenses or the up to 20m thick overlying clays could have resulted in a large amount of material failing into the pit and disrupting operations.
Initially the sand lens stood 10 m high at the design bench face angle of 80 degrees. With exposure to runoff they eroded (Photograph taken in September 2009).

The first lenses observed were typically narrow, less than 2-3 m wide, and up to 10 m to 20 m (one to two benches) high. The sand was fine grained, and poorly graded. Back analyses of fresh sand faces and multi bench sand faces, conducted in September 2009, indicated that the sand could be described with a linear strength of cohesion $c' = 20$ kPa and friction angle $\phi = 30$ degrees. The use of late summer / early fall geometries of September were used to help justify the assumption that contribution of freezing to the stability of the sand faces was temporarily minimal, and that the steep face angles was due to weak cementation and dry conditions only. No thermistors were ever installed in the River Sand Lens, and the authors recognize that they cannot definitively explain exactly why the cohesion in the sands occurs.

The River Sand Lens was exposed on the 130 m level bench in October 2009, extended over 100 m, and was bound by thin amounts of weathered kimberlite and then competent limestone on its margins (Figures 4 and 5).
It was understood that this River Sand Lens would erode, based on the performance of the smaller and narrower sand exposures. The erosion of the sand to an angle of repose of 30 degrees or flatter would undercut the overlying glacio-marine clays and result in failure of those materials into the pit. This was identified as an unacceptable risk to the project.

4 Remedial measures considerations and options matrix

The remedial measures considered in the evaluation included; water diversions, slope flattening, laybacks, various types of buttresses and rip rap (Wyllie, Mah, 2004 and Read, Stacey, 2009. In order to assist with the decision process, these remedial measures were organized in the form of a decision matrix (Figure 6) that was used to address exposed or possible future sand zone exposures, taking into account their size, access conditions, and location in relation to the overburden slopes and ramp.

The conditions that were assumed in all cases included: ongoing dewatering of the open pit, a perimeter ditch to control run-off at the crest, and additional in-pit run-off control and diversion would be installed, as required. Over the course of 2010, Victor Mine did complete a perimeter ditch, as well as localized run-off control measures.

With respect to the River Sand Lens, design meetings were held in late 2009 and cost estimates for various options were considered and compared. The base case was considered to be the time and costs of doing a layback, namely re-establishing the pit crest such that the slope through the river sand was at 30 degrees, unbenched, and the overlying clays sloped at from 2.5H:1V to 4H:1V, unbenched, with a maintenance berms at both the base of the clays and base of the sand lens. The base case layback was considered to be feasible and could be carried out completely in-house with the mine equipment and operators.
Figure 6. Sand Lens Remediation Options Matrix.

The construction of the layback would conflict with the location of the perimeter dewatering wells, the in-progress perimeter water diversion ditch and access roads behind the pit crest would also need to be laid back, which would be disruptive on many accounts. The costs to move these parts of the mine infrastructure were also considered in the assessment of the layback option.

Furthermore, the cost comparison for each remediation option had to consider the specifics of the Victor Mine. For example, the site has limited access for heavy equipment or materials, as the winter road is only accessible during the months of February and March. The alternative method of delivery, cargo plane, would be cost prohibitive.

There was consensus on the following, with respect to sand zone exposures:

- New exposures should be remediated as soon as practical to control erosion and prevent step-ins that could potentially sterilize ore;
- The Victor Mine should have more than one way to safely mine and maintain slopes through existing and future sand exposures;
- Some trials would be required, as many of the solutions have not been previously attempted in an open pit environment;

Notes: For all sand lens remediation,
- Always seal the top of the impacted bench using a geomembrane or low permeability fill such as soil cement, light concrete or cemented rockfill.
- Carry out remediation while bench is still easily accessible and ideally before erosion has occurred.
- Take into account future access, or lack of, and trafficking on top of the bench when selecting a remediation measure. Trafficked benches and benches that will become inaccessible will require more robust solutions.
- Measures based on the assumption that perimeter ditches will be installed, with surface water directed away from the bench crest.
• Remedial measures could involve a combination of various options;
• Access at the based on the overburden slopes should be preserved for future maintenance purposes in case localized instabilities were to occur; and
• Despite the implementation of some of the remedial measures, the overall slope stability within the sand zones could be compromised if these zones are too wide (> 40 m) and extend for several benches (say > 20 m).

Under these conditions, large sand zones may need to be treated as sand slopes with a much shallower inter-ramp angle.

5 Case study – The River Sand Lens

The various options presented on Figure 6 and in Section 4 were carefully considered for the River Sand Lens. With reference to the “Sand Lens Remediation Options Matrix”, the River Sand lens is considered a feature where a robust solution was required, as:

• It is located in an area of potentially high impact, because it underlies a 20m thick marine clay slope and overlies a ramp.
• The lens is wide. Located on the 130m level bench, 100m wide and at the time of the first assessment, believed to be entirely single bench, 10m high.

Mining constraints included a need to avoid a layback and a desire to avoid a step-in that would potentially sterilize ore. Consequently, various soil slope stabilization methods more typical of civil engineering projects were identified as required, to provide a site specific, robust solution. Many options were quickly ruled out because of the specialized equipment or mass of materials that would need to be brought to site.

Some of the buttressing measures that were considered are common place in Civil Engineering projects, but lack in case histories of their application to the mining environment, including questioning about the potential impact of future near-by blasting and the specialized equipment required was a concern.

The preferred solution was to buttress and cover the 100 m long, 10 m high sand lens on the 130 m level, rather than layback the slope. Discussions with vendors narrowed the choice down to a gabion basket wall type solution or a mechanically stabilized earth (MSE) solution.

Both solutions had the appeal of requiring relatively light materials: gabion baskets or geotextile reinforcement mesh and facing, respectively that could be flown to site. Local waste rock could be used to fill the gabion baskets while the coarse processed kimberlite sand produced in the plant could be used as a native fill for the MSE wall. The mine had experience with the processed kimberlite, as it was already being used as a construction material for a fine processed kimberlite impounding rink dyke. This existing experience was the deciding factor in selecting the MSE retaining wall option. A vendor was retained by the mine to supply the materials and provide a basic design. The wall was to be constructed by a specialist contractor, with supervision by Victor Mine operations staff, and quality control and quality assurance monitoring by Golder Associates Ltd.

Construction of the MSE wall on the 130 m bench began in the summer of 2010, concurrent with ongoing mining activities. The MSE design called for a 5 m deep retaining wall, constructed in lifts to a height of 7.3 m, then covered with backfill sloped at 2H:1V. This arrangement conformed to the MSE wall vendor’s limit equilibrium factor of safety of 1.5 for resistance against block sliding, under dry conditions.

In order to fit this MSE wall onto the 130 m bench, the catch berm width was locally widened by carefully removing some of the sand lens and by locally reducing the catch berms below the 130m bench, with purpose to maintain the design inter-ramp angle of 45 degrees.

Construction took place between July and November 2010. Early in August, it became apparent that the southern 30 m of the sand lens were extending for two benches or 20 m deep to the 140m level. However, some
initial lifts on the 130 m level had already been placed across this interval. Re-design discussions were initiated and the vendor’s engineers recommended that to properly buttress a 20 m high zone to 1.5 FoS against block sliding, a single MSE wall, founded on the 140 m bench, with width on the order of 12 m would be required. Operationally, this solution would have been very disruptive to implement.

The vendor was reluctant to endorse the alternate solution, which was eventually implemented, of a two MSE wall solution, with the a 7.3 m high MSE wall buttress constructed on the lower bench first, 140 m level, then the completion of the upper MSE wall on the 130 m bench next, now that the lower slope was controlled. Stability analyses indicated that this solution had a worst case FoS=1.3 (Figure 7) against block sliding, which did not bee the vendor’s acceptance criteria.

Figure 7. Block sliding analyses for two benches in River Sand Lens Remediation Options Matrix.

The Figure 7 stability analysis results were presented to Victor Mine Engineering as a rationale for proceeding with the two benched, two MSE wall solution along with detailed discussions of the understanding of the material properties and failure modes of the slope and MSE wall system, for which sliding failure was the failure mechanism with the lowest safety factor for support. This included assessments of the risk associates with failure of the MSE wall. The main purpose of the system is to reduce erosion of the River Sand Lens and the overlying clay. If it fails to do so, the mine will have time to control erosion by other means. A prism on the MSE wall monitors for movement. Failure of the MSE wall would most likely only occur post-closure, when dewatering ceases and the local water table resaturates the sand. When asked by Victor Mine geotechnical engineering staff for a literature based acceptance criteria to complement the engineering assessment and limit equilibrium FoS=1.3 for this situation, the authors cited Table 1.1 of the Guidelines for Open Pits (Read and Stacey, 2009).

On this basis the criteria were agreed upon by Victor Mine and Golder. Figures 8 and 9 are photographs of the completed MSE walls.
2011 Performance of the two-bench MSE wall and other sand lenses

In 2011, there was a significant improvement in the performance of the overlying clays, because of the perimeter ditch and water diversion controls. This included in local areas, diversion ditching at the base of the clay slope to keep clay slope run-off from flowing uncontrolled over the narrow sand lenses within the limestone bedrock slope below. No significant erosion events were observed during the spring freshet or subsequent heavy precipitation events. The MSE walls and sloped rip rap diverted direct precipitation away from the river sand.
No slope movement was observed based on prism monitoring. As shown on Figure 10 there has been some
ravelling of the MSE wall rip-rap cover, which is a rock fall hazard concern.

Several rock falls from the 140m, 150m and 160m level bench were noted to be reaching the pit floor below. While some rock fall can be expected, the limestone slope design below the MSE wall / River Sand slope, which called for a 55 degree inter-ramp angle and single, 10m high benches, required that the design catch bench width be 6 m. Between the MSE wall and the ramp below, some benches were designed slightly narrower, to allow for a suitable bench width at the 140m level, while maintaining the overall design. This combined with local break back has resulted in some catch berms of widths 5m or less. Remedial measures under consideration to reduce rock fall hazard at the ramp below have focused on widening the ramp and constructing a rock fall catch zone which will include either a catch fence or berm for additional protection. Double benching to increase the catch bench width is also under discussion.

Figure 10. View of completed MSE wall, 140m bench, photo taken by Jin Dong Du, Victor Mine Engineering Group, April 2011. The inset image shows over-steep rip rap spilling off the MSE wall. Operating pit floor is at the 170m bench level at the time of the photograph.

7 Conclusions

Overburden slopes, such as the clays and sands at Victor Mine, exposed on pit slopes in sub-arctic environments are highly susceptible to degradation and erosion due to run-off, freeze thaw and precipitation. As much as practical, water management and water diversion must be built into the slope design up front.

The 2011 positive slope performance of the overlying clays and narrow sand lens zones, thanks to the remedial water diversions is telling. Some of the erosion problems in 2009 and 2010 would have been reduced had these been implemented sooner. The prevention of uncontrolled runoff flow would also have helped reduce the rate of erosion of the unexpected sand lenses intercepted in the upper bedrock, possibly allowing more time for remedial measures for the large sand lenses to be considered.
With respect to the MSE walls constructed to control erosion of a very large river sand exposure, final construction costs were found to be approximately equal to the estimated cost of a layback, indicating that the solution was economic. The MSE wall construction was a learning experience for Victor Mine and the contractor, neither of whom had had previous experience with carrying out this sort of in-pit construction during operations.

8 Acknowledgements

The authors are grateful to the management of the Victor Mine (De Beers Canada Inc) for permission to publish this paper on stabilizing unexpected sand lenses on pit slopes in disturbed limestone with an MSE wall. In particular, the authors would like thank Mr. Paul Gauthier for his leadership and support, and to Mr. Jin Dong Du for his assessments and observations of the geotechnical performance of the slopes at Victor Mine.

The successful construction of the buttress MSE wall on two benches is due in large part to the mine staff that contributed to the engineering judgement that aided successful implementation of the support measures. Recognition must also be given to the field staff that actually achieved the often challenging construction requirements.

9 References


